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Analysis of Direct Torque Controlled Techniques for Induction Motor Drives with Two Level Inverter

Abhishek Verma, Yogesh Kumar Chauhan

***Abstract*— The objective of the present work is to obtain the reduced torque ripples, harmonics distortion. Duty Ratio Control has been developed to improve the torque performance and to obtain the voltage space vector required to compensate the flux and torque errors. In conventional Direct Torque Control (DTC), the selection of flux linkage and electromagnetic torque errors are made within the respective flux and torque hysteresis bands, in order to obtain fast torque response, low inverter switching frequency and low harmonic losses. However, DTC drives utilizing hysteresis comparators suffer from high torque ripple and variable switching frequency. As in duty ratio control technique, instead of applying a voltage vector for the entire switching period, it is applied for a portion of the switching period and the zero switching state is applied for the rest of the period the ripples is considerably reduced. In this paper the simulation of different DTC schemes (Conventional DTC and Duty Ratio Control DTC) has been carried out using MATLAB/SIMULINK and the results are compared.**

***Index Terms*—ABB Company, Asynchronous motor, Direct torque control, Simulation, Torque ripple.**

I. INTRODUCTION

Direct torque control (DTC) drives are finding great interest, since ABB recently introduced the first industrial direct-torque-controlled induction motor drive in the mid-1980's, which according to ABB can work even at zero speed. This is a very significant industrial contribution, and it has been stated by ABB that ''DTC is the latest AC motor control method''. ABB has also introduced a DTC based medium voltage drive called the ACS1000, thus feeding pure sinusoidal voltages and currents to the motor. This is ideal for pumps and fans [1].

With the revolutionary DTC technology developed by ABB, field orientation is achieved without feedback using advanced motor theory to calculate the motor torque directly and without using pulse width modulation. The controlling variables are motor magnetizing flux and motor torque**.** With DTC there is no modulator and no requirement for a tachometer or position encoder to feed back the speed or position of the motor shaft. DTC uses the fastest digital signal processing hardware available. The result is a drive with a torque response that is typically 10 times faster than any AC or DC drive [2].

The Conventional DTC method yields slow response during start up and change in either direction of torque and flux. In addition to this, also high torque ripples are found. Several techniques have been developed to improve the torque performance. One of them is to reduce the ripples using Duty Ratio Control Technique[3]. In Duty Ratio Control Technique instead of applying a voltage vector for the entire switching period, it is applied for a portion of the switching period and the zero switching state is applied for the rest of the period the ripples can be reduced. This is defined as duty ratio control in which the portion of the switching period for which a nonzero voltage vector is applied is known as the duty ratio Δ.

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II. ASYNCHRONOUS MOTOR MODEL

A. Axes Transformation

Consider a symmetrical three-phase induction machine with stationary $a_s - b_s - c_s$ axes at 2π/3 angle apart, as shown in Fig. 1.

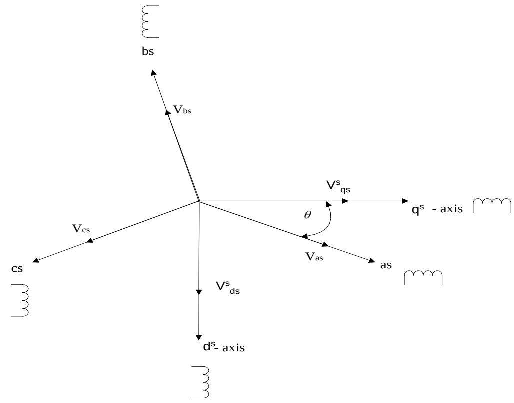

Fig. 1 Stationary frame $a-b-c$ to $d^s - q^s$ axes transformation

The main goal is to transform the three-phase stationary reference frame ($a_s - b_s - c_s$) variables into two phase stationary reference frame ($d^s - q^s$) variables and then transform these to synchronously rotating reference frame ($d^e - q^e$), and vice versa. Assume that the $d^s - q^s$ axes are oriented at 'θ' angle shown in Fig. 1. The voltages V^s_{ds} and V^s_{qs} can be resolved into $a_s - b_s - c_s$ components can be represented in the matrix form as:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120^o) & \sin(\theta - 120^o) & 1 \\ \cos(\theta + 120^o) & \sin(\theta + 120^o) & 1 \end{bmatrix} \begin{bmatrix} V^s_{qs} \\ V^s_{ds} \\ V^s_{os} \end{bmatrix} \quad (1)$$

The corresponding inverse relation is:

$$\begin{bmatrix} V^s_{qs} \\ V^s_{ds} \\ V^s_{os} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120^o) & \cos(\theta + 120^o) \\ \sin\theta & \sin(\theta - 120^o) & \sin(\theta + 120^o) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad (2)$$

where, V^s_{os} is added as the zero sequence component, which may or may not be present. The voltage has been considered as the variable. The current and flux linkage can be transformed by similar equations. It is convenient to set θ = 0, so that the q^s-axis is aligned with the as-axis. Ignoring the zero sequence components, the transformation relations can be simplified with the help of equations (1) and (2) by assuming θ = 0 in these respective equations as:

$$V_{as} = V_{as} \tag{3}$$

$$V_{bs} = -\frac{1}{2}V_{qs}^{s} - \frac{\sqrt{3}}{2}V_{ds}^{s} \tag{4}$$

$$V_{cs} = -\frac{1}{2}V_{qs}^{s} - \frac{\sqrt{3}}{2}V_{ds}^{s} \tag{5}$$

and inverse equations are expressed as:

$$V_{qs}^{s} = \frac{2}{3}V_{as} - \frac{1}{3}V_{bs} - \frac{1}{3}V_{cs} = V_{as} \tag{6}$$

$$V_{ds}^{s} = -\frac{1}{\sqrt{3}}V_{bs} + \frac{1}{\sqrt{3}}V_{cs} \tag{7}$$

B. Modelling

An induction motor is modelled using voltage and flux equations which are referred to synchronous rotating reference frame, denoted by the superscript e.

Induction motor model: Voltage and flux linkage; mechanical torque equation as:

$$V_s^e = R_s\, i_s^e + j\omega_e\, \lambda_s^e + d/dt(\lambda_s^e) \tag{8}$$

$$0 = R_r\, i_r^e + j\,(\omega_e - \omega_r)\, \lambda_r^e + d/dt(\lambda_r^e) \tag{9}$$

$$\lambda_s^e = L_s\, i_s^e + L_m\, i_r^e \tag{10}$$

$$\lambda_r^e = L_r\, i_r^e + L_m\, i_s^e \tag{11}$$

$$T_e - T_L = J_m\, p\, \omega_r + B_m\, \omega_r \tag{12}$$

$$T_e = \frac{3P}{2}(\lambda_{sd}^e\, i_{sq}^e - \lambda_{sq}^e\, i_{sd}^e) \tag{13}$$

By referring to a stationary reference frame, denoted by the superscript s, with d-axis attached on the stator winding of phase A, the mathematical equations of induction motor can be rewritten as follows.

$$V_s^s = R_s\, i_s^s + d/dt\lambda_s^s \tag{14}$$

$$0 = R_r\, i_r^s - j\omega_r\lambda_r^s + d/dt\, \lambda_r^s \tag{15}$$

$$\lambda_s^s = L_s\, i_s^s + L_m\, i_r^s \tag{16}$$

$$\lambda_r^s = L_r\, i_r^s + L_m\, i_s^s \tag{17}$$

$$T_e = \frac{3P}{2}\frac{L_m}{\sigma L_s L_r}(\lambda_{sd}^s\, i_{rq}^s - \lambda_{sq}^s\, i_{rd}^s) \tag{18}$$

All of the above equations explain the modelling of induction motor in synchronous reference frame and stationary reference frame.

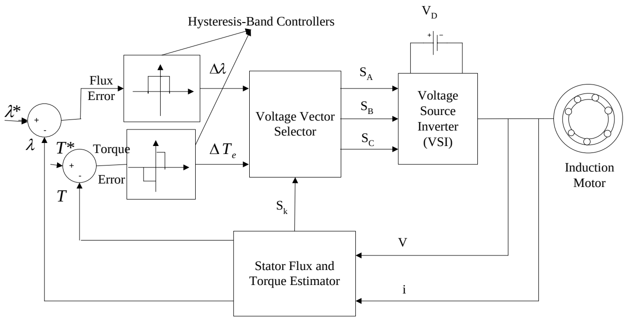

Fig. 2 Conventional DTC drive configuration

III. Conventional DTC

In addition to vector control systems, instantaneous torque control yielding very fast torque response can be obtained by employing DTC. Drives with direct torque control DTC are finding great interest, since in the mid of 1980's, 'ABB' introduced the first industrial direct-torque-controlled induction motor drive. In a DTC drive, flux linkage and electromagnetic torque are controlled directly and independently by the selection of optimum inverter switching modes. The selection is made to restrict the flux linkage and electromagnetic torque errors within the respective flux and torque hysteresis bands, to obtain fast torque response, low inverter switching frequency and low harmonic losses. The required optimal switching voltage vectors can be selected by using a so called optimum switching voltage vector look-up table. This can be obtained by simple physical considerations involving the position of the stator flux linkage space vector, the available switching vectors and the required torque and flux linkage. In the Fig. 2, Configuration of Conventional DTC drive is shown, in which the comparison between the reference and the actual value is taken and the errors are processed through hysteresis band controllers. The flux loop controller has two levels of digital output and the torque control loop has three levels of digital output. The feedback flux and torque are calculated from the induction machine terminal voltages and currents. The three phase terminals quantities are converted into two phase stationary $d-q$ components, which are used for estimating motor torque and stator linked flux. Based on the resultant flux position and the errors in flux magnitude and in torque, a three-dimensional look up table is referred to decide the inverter switching. The 'Stator Flux and Torque Estimator' block shown in Fig. 2 gives the sector number S_k (in which the flux vector λ lies) which is fed to the 'Voltage Vector Selector' block.

C. Look Up Table Selection

The required stator flux is maintained by means of choosing the most suitable VSI state. If the ohmic drop is neglected, then the stator voltage impresses directly the stator flux in accordance with the equation given as:

$$\frac{d}{dt}\vec{\lambda}_s = \vec{V}_s \quad \text{or} \quad \Delta\lambda_s = \vec{V}_s\, \Delta t \tag{19}$$

Decoupled control of the stator flux and torque is achieved by using radial and tangential components of the stator flux linkage space vector in its locus. These two components are directly proportional to the components of the same voltage space vector in the same directions. Fig. 3 shows the possible dynamic locus of the stator flux, and its variation depending on the chosen VSI states. The possible global locus is divided into six different sectors shown by the discontinuous line. From Fig. 3, the general table can be framed. It can be seen from the Table 1 that the states V_k and V_{k+3}, are not considered in the torque because they can both increase (initial 30º) or decrease (next 30º) the torque at the same sector depending on the stator flux position.

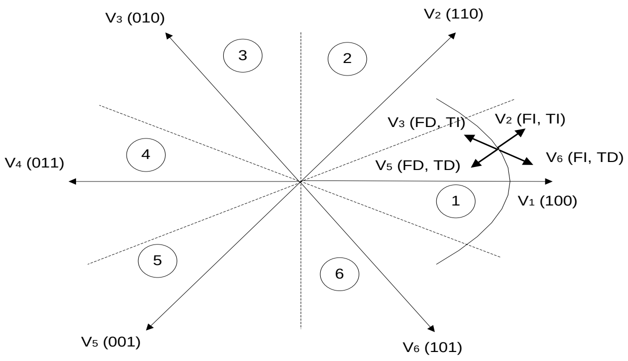

Fig. 3 Stator flux vector locus and different possible switching voltage vectors

FD: Flux Decreases, FI: Flux Increases TD: Torque decreases, TI: Torque Increases.

Finally, The DTC classical table is as follows:

TABLE I

SWITCHING VECTOR SELECTION TABLE

λ	T	S_1	S_2	S_3	S_4	S_5	S_6
FI	TI	V_2	V_3	V_4	V_5	V_6	V_1
	TE	V_0	V_7	V_0	V_7	V_0	V_7
	TD	V_6	V_1	V_2	V_3	V_4	V_5
FD	TI	V_3	V_4	V_5	V_6	V_1	V_2
	TE	V_7	V_0	V_7	V_0	V_7	V_0
	TD	V_5	V_6	V_1	V_2	V_3	V_4

FD/FI: Flux decreases/Increases.
TD/TE/TI: Torque decreases/equal/Increases.

where, S_k stator flux sector; λ stator flux modulus error after the hysteresis block; T torque error after hysteresis block.

The sectors of the stator flux space vector are denoted from S_1 to S_6. Stator flux error after the hysteresis block can take three values. The zero voltage vectors V_0 and V_7 are selected when the torque error is within the given hysteresis limits, and must remain unchanged.

IV. DUTY RATIO CONTROL STRATEGY

Another major concern in direct torque control induction motor drive are torque and flux ripples since none of the inverter switching vectors is able to generate the exact stator voltage required to produce the desired changes in torque and flux. Possible solutions involve the use of high switching frequency or change in inverter topology, these solutions increases switching losses and increase cost. The induction motor stator flux and torque in the stationary reference frame are given by:

$$\psi_{qs} = \int (V_{qs} - r_s\, i_{qs})\, dt \tag{20}$$

$$\psi_{ds} = \int (V_{ds} - r_s\, i_{ds})\, dt \tag{21}$$

$$T_e = \psi_{ds}\, i_{qs} - \psi_{qs}\, i_{ds} \tag{22}$$

$$\theta = \tan^{-1} \frac{\psi_{qs}}{\psi_{ds}} \tag{23}$$

$$\psi_s = \sqrt{(\psi_{ds}^2 + \psi_{qs}^2} \tag{24}$$

$$V = \Delta V_{dc} \tag{25}$$

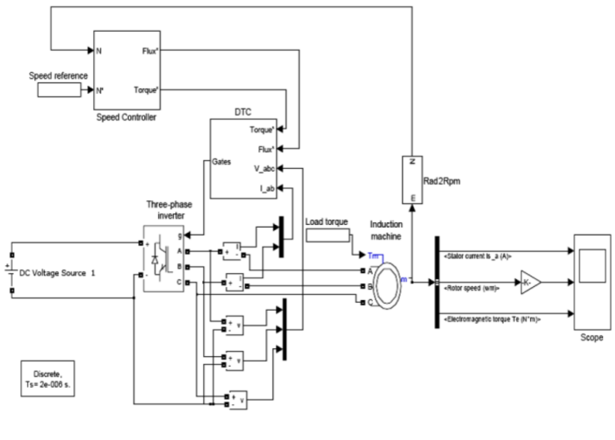

Fig. 4 Simulation of Conventional DTC

Equations 20 to 25 are used in the direct self-control to estimate the stator flux and the electric torque T_e in the machine. The estimated values of the stator flux and torque are compared to their command values (ψ_{ref} and T_{ref} respectively) and the inverter switching states are selected according to Table I. It can be seen from equations 20 to 25 that, the changes in torque and flux are functions of input voltage and the inverter switching time. The ripple can, therefore, be reduced either by reducing the input dc voltage amplitude or the switching time. At low input dc voltage the range of speeds in which machine can operate, become small. At higher speeds the emf generated in the machine increase to a level, where the input voltage would no longer be able to generate the required torque and flux regulation. Thus using low voltage levels is not desirable for the machine operation. Fuzzy Implementations

The voltage vectors selected from the fuzzy DTC are not optimal in some region of stator flux vector positions. These disadvantages are improved by the fuzzy controller called a duty ratio controller. Since the duty ratio during each switching state is a nonlinear function of number of factors: torque error ($E_{te} = T_{ref} - T_e$) , flux error $E\psi = \psi_{ref} - \psi_e$ and flux position (θ), it is difficult to mathematically model its relation between the three variables. The fuzzy logic control seems to be a reasonable choice to determine the duty ratio during each switching state. Fuzzy logic converts a set of linguistic rules based on expert knowledge into an automatic control strategy. In this control the selected inverter switching state is applied for a portion of the sample period, defined as a duty ratio Δ, and the zero switching state is applied for the rest of the period. The duty ratio is chosen to give an average voltage vector, which causes torque change with ripple reduction. Fuzzy controller includes three inputs (torque error E_{te}, flux error E_λ, and the position of the stator flux linkage according to corresponding sector) and one output (duty ratio Δ). Fig. 5 describes membership function for inputs and output. The fuzzy logic controller is a Mamdani type and contains a rule base. This base comprises of two groups of rules, each of which contains nine rules. The first group is used when the stator flux linkage modulus is smaller than its reference value (Table II), and the second group of rules is used when it is greater than its reference value (Table II). There are together 18 simple rules and only three fuzzy sets

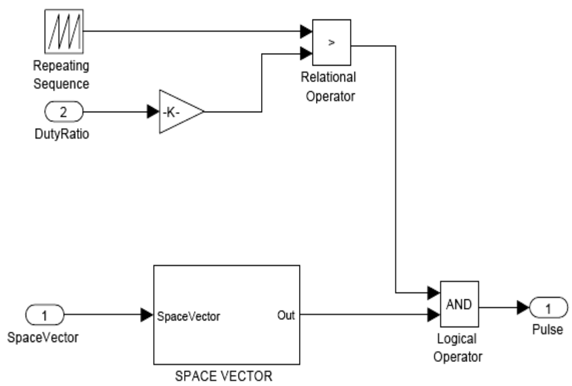

Fig. 5 Generation of switching pulses

D. *Fuzzy Rule-Base*

As shown in Fig 7, the fuzzy duty ratio controller gives duty ratio (Δ) as its output. For the generation of the switching pulses, the duty ratio is multiplied with the DTC sampling period and then it is compared with a triangular wave which has also the amplitude equal to the sampling period and frequency equal to sampling frequency of DTC. Finally the comparator output gives the pulse to the inverter as shown in Fig.5 in order to generate optimum voltage vector.

The FIS Editor, the Membership Function Editor, the Rule Editor, and the Rule Viewer of the fuzzy controller are used here. The Membership Function Editor is used to define the shapes of all the membership functions associated with each variable. The Rule Editor is for editing the list of rules that defines the behaviour of the system. The Rule Viewer is a MATLAB based display of the fuzzy inference diagram, used as a diagnostic it shows which rules are active and how individual membership function are influencing the results. The Surface Viewer is used to display dependency of one of the outputs on any one or two of \ the inputs that is, it generates and plots an output surface map of the system.

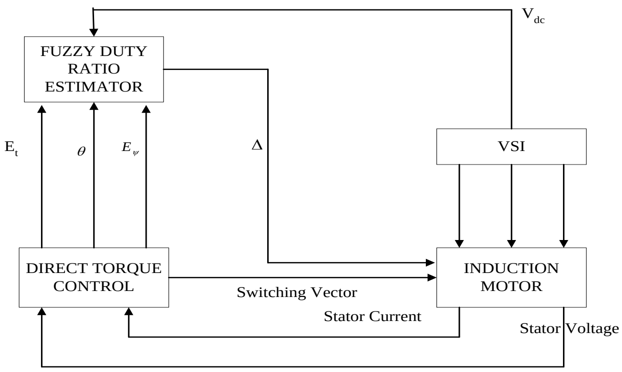

Fig. 6 Block Diagram of Duty Ratio Controller DTC

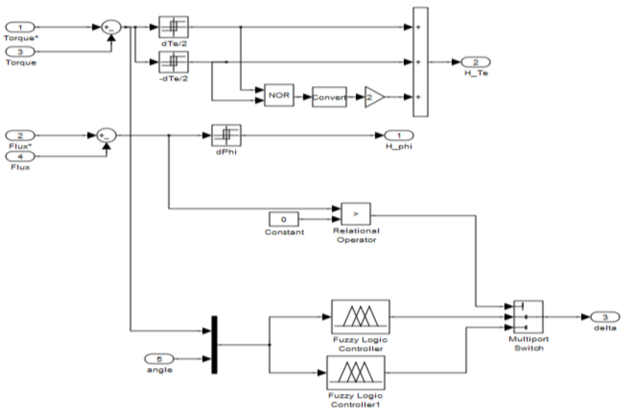

Fig. 7 Fuzzy Rules for Duty Ratio Control

TABLE II

FUZZY RULES FOR DUTY RATIO CONTROL

Group 1 Rules	Group 2 Rules
If E_{te} is small and θ_s is small then δ is medium.	If E_{te} is small and θ_s is small then δ is small.
If E_{te} is small and θ_s is medium then δ is small.	If E_{te} is small and θ_s is medium then δ is small.
If E_{te} is small and θ_s is large then δ is small.	If E_{te} is small and θ_s is large then δ is medium.
If E_{te} is medium and θ_s is small then δ is medium.	If E_{te} is medium and θ_s is small then δ is medium.
If E_{te} is medium and θ_s is medium then δ is medium.	If E_{te} is medium and θ_s is medium then δ is medium.
If E_{te} is medium and θ_s is large then δ is medium.	If E_{te} is medium and θ_s is large then δ is large.
If E_{te} is large and θ_s is small then δ is large.	If E_{te} is large and θ_s is small then δ is medium.
If E_{te} is large and θ_s is medium then δ is large.	If E_{te} is large and θ_s is medium then δ is large.
If E_{te} is large and θ_s is large then δ is large.	If E_{te} is large and θ_s is large then δ is large.

V. SIMULATION RESULTS

The control scheme is simulated with Matlab/Simulink, for following case as:

In Conventional DTC:

- The speed reference prescribed to (800; 1000) rpm at t = (0; 1.5) s,
- The load torque prescribed to (0; 12) Nm at t = (0; 1.5) s with step variation.

The speed reference prescribed to (800; 1000) rpm at t = (0; 1.5) s, the load torque prescribed to (0; 10; 20) Nm at t = (0; 0.5; 1.5) s with step variation. Fig. 9(a) and 9(b) shows the speed torque responses of the induction motor at different conditions i.e. the constant speed command 800 rpm is given for 0 to 1.5 seconds and the load torque is changed at 0.5 second from 0 to 10 Nm. From 1 to 1.5 seconds the load torque is maintained at 10 Nm, but the speed command is changed at 1.5 second from 800 rpm to 1000 rpm. Also at 1.5 second the load torque is changed from 10 Nm to 20 Nm. From the fig 9(b) we can see that if the speed command is changed suddenly then the induction motor produces a large electromagnetic torque, which is undesirable. From Fig. 9(d), we can see that the torque ripple in case of conventional DTC is ± Nm.

From Fig 10(d), we can see that the torque ripple in duty ratio controlled DTC is ± 3, which is very much less as compared to conventional DTC.

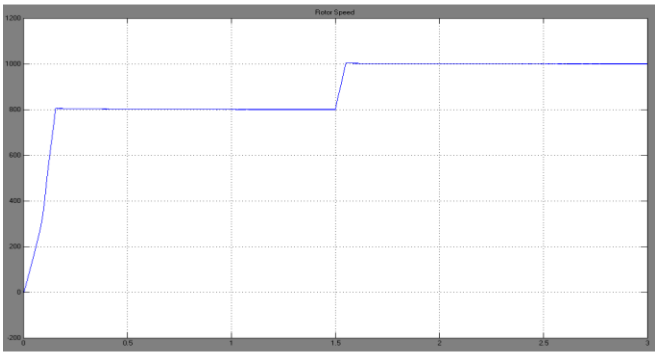

Fig. 9(a). Rotor Speed (rpm) v/s Time (second)

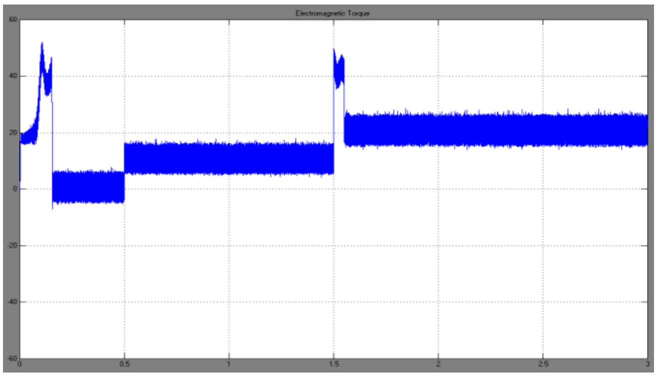

Fig. 9(b). Electromagnetic torque (Nm) v/s Time (second)

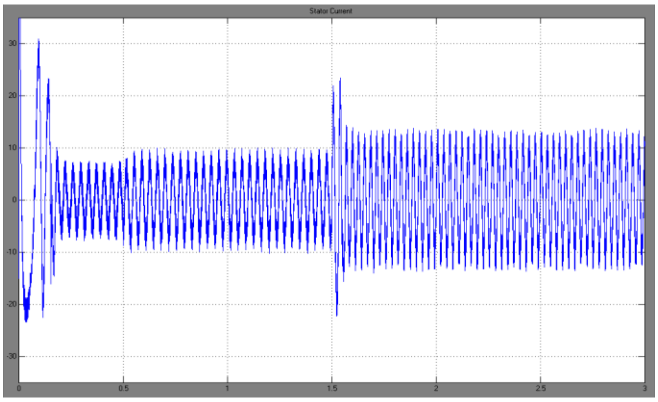

Fig. 9(c). Stator current (ampere) v/s Time (second)

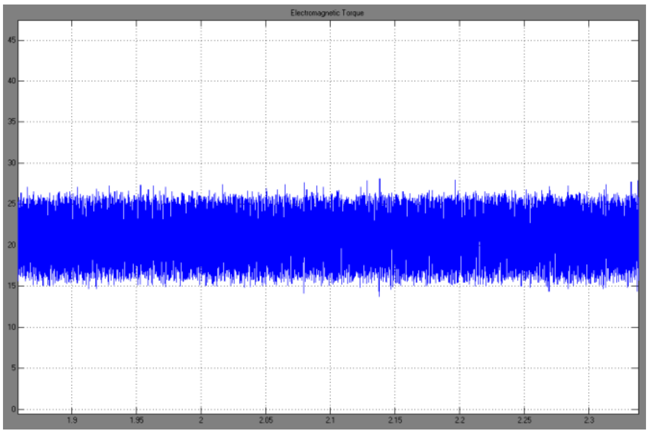

Fig. 9(d). Torque ripples in conventional DTC

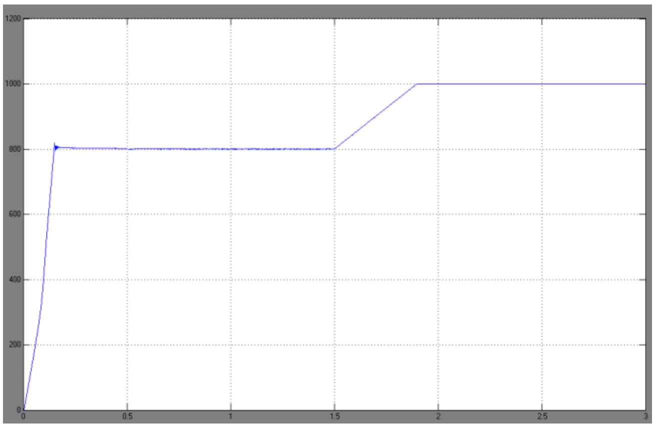

Fig. 10(a). Speed (rpm) v/s Time (second)

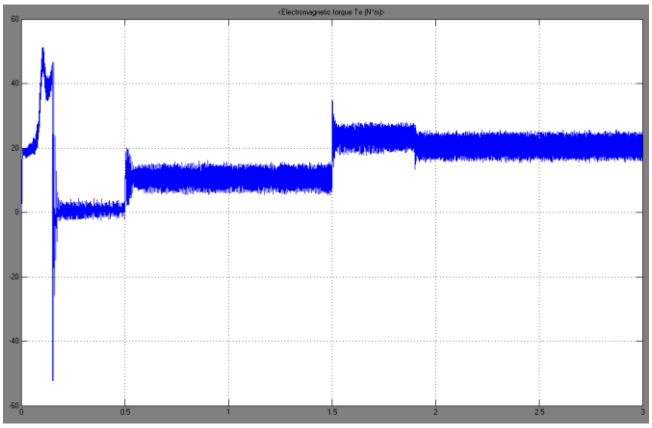

Fig. 10(b). Torque (Nm) v/s Time (second)

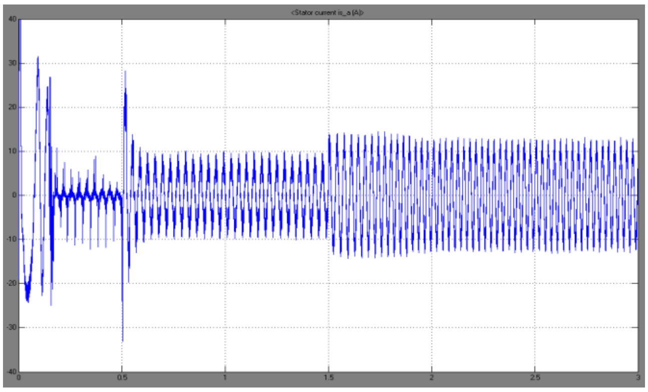

Fig. 10(c). Stator Current (Ampere) v/s Time (second)

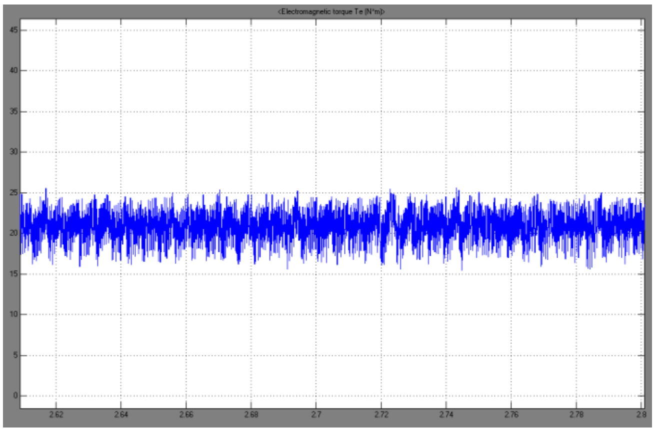

Fig. 10(d). Torque ripples in duty ratio control.

VI. CONCLUSIONS

This Paper presents a comparative study of different direct torque control strategies of induction motor drive based on their simulation results. Two direct torque control strategies (Conventional DTC and Duty Ratio Control) are compared. A comparative analysis among the conventional direct torque control and duty ratio control, strategies are made by simulation in MATLAB/SIMULINK.

Based on simulation results, it can be seen that the ripple in torque with duty ratio control is less than the one with conventional DTC. The effects of the duty ratio controller on the stator flux and current are also presented. As seen there are improvements in the waveforms of duty ratio control compared to the conventional DTC.

The following conclusion can be made,

- Steady State torque ripple is considerably reduced. As from simulation results we can see that the torque ripple present in duty ratio controlled DTC ($\pm$3), which is much less as compared to conventional DTC (± 5)
- It provides fast torque response and better speed accuracy than the conventional strategy.
- Ripples of stator current in the case of Duty Ratio Controller have reduced.

APPENDIX

Power Rating	:	10 HP
Stator Voltage	:	460 volt
Frequency	:	60 Hz
Number of Poles	:	4
Stator Resistance	:	0.6837 ohm/phase
Stator leakage Inductance	:	0.004152 H/phase
Rotor Resistance	:	0.451 ohm/phase
Rotor leakage Inductance	:	0.004152 H/phase
Mutual Inductance	:	0.1486 H
Inertia	:	0.05 kg m^2
Friction Coefficient	:	0.0081412

ACKNOWLEDGMENT

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